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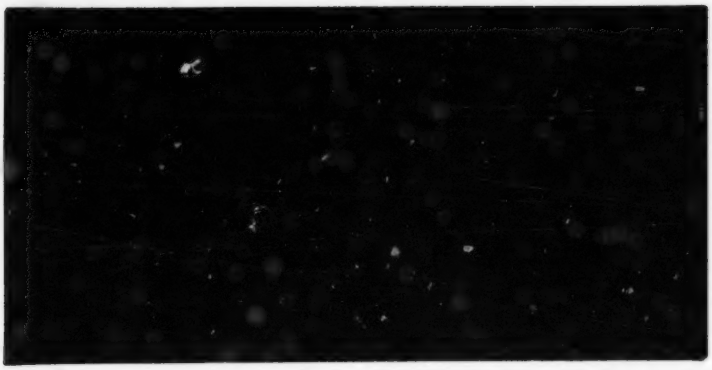
ENFOR Project C-172

Development of Analytical Methodology for Biomass Gasification Products

by

E.C. McDonald, M. Aiken and G. Esplin



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ENFOR Project C-172

Development of Analytical Methodology for Biomass Gasification Products

by

E.C. McDonald, M. Aiken and G. Esplin

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October 1983

DEVELOPMENT OF ANALYTICAL METHODOLOGY FOR BIOMASS GASIFICATION PRODUCTS ENFOR PROJECT No. C-172

ABSTRACT OF THE ABSTRACT

A methodology for sampling and analytical procedures was developed which achieved accurate mass and energy balances of biomass gasification processes.

DEVELOPMENT OF ANALYTICAL METHODOLOGY FOR BIOMASS GASIFICATION PRODUCTS ENFOR PROJECT No. C-172

ABSTRACT

To calculate the conversion efficiency of biomass gasification processes, it is necessary to measure the flow rate, composition and energy content of the various streams entering and leaving the gasifier system. Concurrent calculation of mass balances and energy balances allows an evaluation to be made of the accuracy of these measurements.

Conventional stack sampling trains are unsuitable for sampling the high temperature gases and/or high tar concentrations associated with biomass gasification. Consequently, a gasifier sampler was designed and sampling and analytical procedures were developed. The sampler and procedures are described in the ENFOR document "A Workbook for Biomass Gasification Sampling and Analysis". This workbook methodology has been proven applicable to both fluidized bed and downdraft gasifiers. Accurate mass and energy balances were achieved for these biomass gasification processes.

The application of the workbook methodology to the Forintek downdraft gasifier is described in the ENFOR document "Testing the Prototype Sampler on an Downdraft Biomass Gasifier".

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STAFF

B.C. Research personnel from the Environment and Health Division and the Chemical Technology Division carried out the work under contract to Techwest Enterprises Ltd.

The gasifier sampler was designed by Mr. Gordon Esplin, the Project Manager. Assembly and testing of the sampler was carried out by Mr. Merv Aiken.

Development of analytical procedures and chemical analyses of samples were carried out by Ms. Elizabeth McDonald and Ms. Bridie Bennett.

B.C. Research staff involved in operating the B.C. Research fluidized bed gasifier were Dr. Rod McElroy, Dr. Cedric Briens, Mr. Duncan Morgan and Mr. Rick Labram.

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The support and assistance of Dr. David Fung (CANMET), our scientific authority, is gratefully acknowledged.

The sampling survey of the Forintek gasifier was a co-ordinated effort involving personnel from Forintek Canada Corporation in Ottawa and B.C. Research. The assistance of the following Forintek personnel was appreciated: Dr. Don Huffman, Dr. John Kryla, Mr. Art L'Ecuyer, Mr. Ron Therberge, Ms. Bonnie Grant and Mr. Ed Doyle.

We thank Dr. Hughes Ménard, University of Sherbrooke, for the considerable amount of work he has carried out on the analysis of the gasifier tar sample.

1.0 INTRODUCTION

1.1 Objective

To develop a standard procedure for the collection, separation and analysis of raw producer gas from biomass gasification.

To prepare a Workbook which describes the methodology for sampling and analysis of raw producer gas and for the calculation of energy and mass balances for biomass gasification processes.

Specifically, to devise procedures for accurate determination of:

a. Volume rate of raw producer gas.
b. Mass concentrations of gas, liquid and solid components of the above stream.
c. Chemical composition of the gas, liquid and solid phases.
d. Higher heating values of the product components.
e. Mass and energy balances and energy conversion efficiencies for the gasification process.

1.2 Background

Biomass gasifiers convert cellulosic solids to a gas which can be burned directly as a fuel, or can be converted to other products such as methanol and industrial chemicals. To calculate the efficiency of this conversion, it is necessary to measure the flow rate, composition and energy content of the various streams entering and leaving the gasifier system. Concurrent calculation of mass balances and energy balances allows an evaluation to be made of the accuracy of these measurements.

Concerns have been expressed by gasifier operators that a standard method was lacking for systematically collecting, separating and analyzing the raw producer gas from biomass gasification processes. In the past, conventional methods were used by individual operators, but there were serious discrepancies in the results because of a lack of conformity in the procedures for collecting and analyzing the raw producer gas. This has presented problems in the interpretation of results and in the calculation of mass and energy balances of the gasification process.

Conventional stack sampling apparatus was not suitable for extracting samples from streams heavily laden with tar such as those from an updraft gasifier, or for sampling the very high temperature streams (800°C) possible from fluidized bed gasifiers.

Problems associated with the analysis of gasifier products were more a function of the quality of the samples collected than of the analytical procedure utilized. The ability to obtain samples of gas, liquid and solid products as discrete, homogeneous fractions is the key to the successful application of conventional analytical procedures.

To address the above problems B.C. Research, under the auspices of Techwest Enterprises Ltd. and ENFOR Project C-172, undertook to develop a standard procedure for the collection, separation and the analysis of gasifier product streams.

1.3 Preliminary Investigation

As a prelude to the development work an extensive survey of the literature on biomass gasification and pyrolysis system sampling and sample analysis was undertaken. Interviews were held across

Canada with people associated with the operation and analysis of biomass gasifiers in order to determine what problems were encountered in gasifier sampling and analysis, and to receive feedback on the tentative design of the sampler and initial ideas on the parameters required for elementary gasifier material and energy balances.

Discussions were also held with manufacturers of stack sampling apparatus to determine how their equipment could be modified to accommodate the gasifier sampling requirements.

2.0 DEVELOPMENT OF GASIFIER SAMPLER

2.1 Gasifier Sampler Design

Following the preliminary investigation and interviews the ENFOR sampler (Figure 1) was specified to incorporate the following features:

1. Isokinetic conditions can be easily maintained and can be automated if desired. The sampling flow rate is measured with an orifice meter, located immediately after the filter and thus is kept at the filter temperature of 200°C. Hence, a knowledge of producer gas composition is not required prior to sampling and rapid changes in gas moisture content can be accommodated.

2. The probe and cyclone are kept close to stack conditions to prevent a change occurring in the sampled gas. Particulates and aerosols removed by the high-efficiency cyclone are immediately quenched in an air-cooled collection bottle.

3. The gas then passes through a forced convection heat exchanger, where the temperature is brought to a standard value of 200°C. Temperatures lower than this could result in excessive tar buildup on the filter and subsequent plugging, while higher temperatures would result in sample thermal decomposition and a weakening of the filter substrate.

4. The filter diameter (15 cm) is larger than that normally used. Hence, more samples can be obtained for subsequent analysis.

5. Sample gas leaving the orifice meter at 200°C is quenched immediately to 0°C. This is accomplished in a novel, counter-current heat exchanger, which also acts as the sample line to the ice chest. Tar and water condensation occur within the inner Teflon hose. This condensate flows to a collection flask in the ice chest, while the non-condensable gases go through a demister to a drying tube and then to the usual sampling pump and control console.

   At the design flow of 30 standard dry litres/min., a conventional ice-cooled impinger train would be totally inadequate to remove the sensible and latent heat present in the gas stream.

A commercial apparatus, the Aerotherm High Volume Stack Sampler, was purchased and subsequently modified to provide the above design features. Figure 2 illustrates the modified sampler. The probe was altered to operate at temperatures up to 800°C. A new sample box was designed to accommodate the cyclone, the gas conditioning coil and the filter/orifice-meter assembly. All three of these assemblies are located in separate, temperature controlled compartments. The 4.5 metre, counter-current, ice-water cooled condenser tube cools the hot gases and conveys them to the relatively heavy ice-chest/impinger train, which normally is attached to the sample box. The modified design allows this heavy component to be located on the ground along with the conventional vacuum pump and control box.

2.2 Gasifier Sampler Testing

The modified sampler was extensively tested using the B.C. Research fluidized bed gasifier, which was operated so as to maximize tar production. Tests were carried out both in the free-board zone and in the stack of the gasifier.

A detailed description of this development and testing phase is given in the ENFOR document "Development of Sampling and Analytical Procedures for Biomass Gasifiers" (Aiken, 1983).*

Eight different runs (Table 1) were carried out to correct problems in the design and operation of equipment. At the conclusion of this phase the sampler was performing to its design specifications and was shown to be suitable for an elevated temperature gasifier environment.

The major problems encountered during the testing were:

a. Premature tar condensation upstream of the filter occurred in the initial runs. Greater emphasis on preheating of the sampling train components and better temperature control of the train eliminated tar condensation before the filter.

b. Precise temperature control in the sample box was not achieved until the filter temperature controller was found to be faulty and was replaced. In addition, to ensure more efficient operation of the controllers, they were moved to the exterior of the sample box. The temperature controllers required recalibration each time an alteration was made.

c. The orifice plate assembly developed a leak which could not be repaired. Another orifice plate assembly was fabricated.

The results obtained for the overall and element mass balances and energy balances are shown in Table 2.

Reference conditions of 15°C and one atmosphere are used for the energy balances, in accordance with ISO 5024 (ISO, 1977).

* This report is not available for general distribution. However, sampling and analytical procedures are described in the document "A Workbook for Biomass Gasifier Sampling and Analysis" which is available upon request from the ENFOR Secretariat.

The calculation of an energy balance, as per cent closure, allows an evaluation of the accuracy of measurements for all input and output sources of energy.

Two energy conversion efficiencies are calculated. The first, the gross efficiency, reflects the recoverable energy available to a process adjacent to a gasifier. The gross efficiency is defined as the recoverable energy of the raw producer gas divided by the total energy input, expressed as a percentage. The second, the net efficiency, gives the recoverable energy available to a distant process. The net efficiency is defined as the standard higher heat of combustion of the clean, dry gas divided by the total energy input, expressed as a percentage.

Table 3, showing the contributions of the inflow and outflow streams to mass, energy and element balances, provides a wealth of information on which to judge the results for gasifier performance. For example, it permits informed decisions to be made on the relative importance of collecting and analyzing the various fractions in the raw producer gas. For the B.C. Research gasifier, ignoring the measurement and analysis of the moisture content of incoming air, the particulates, the condensate and the tar would still yield a potential overall mass balance of 97%. However, to ignore the tar fraction would seriously affect the energy balance, because the tar contributes 13.5% of the output energy.

The detailed information obtained from the tests carried out on the B.C. Research gasifier was achieved because the sampler design permitted separation of the products into discrete fractions which could be analyzed by conventional standard procedures.

3.0 DEVELOPMENT OF ANALYTICAL PROCEDURES

Initial development work on the analytical procedures was carried out on samples of condensate and tar from the updraft gasifier located at Ainsworth Lumber (Chasm, B.C.). Further testing of procedures for condensate analysis was carried out on a sample of gasifier scrubber effluent provided by the Prince Edward Island Energy Corporation.

The samples obtained during the test sampling runs on the B.C. Research gasifier were used to test, modify and validate the analytical procedures.

It soon became apparent that with partial separation of the producer gas fractions in the sampler, the subsequent separation of the components into discrete, homogeneous samples was relatively simple. Once discrete samples were obtained, standard analytical techniques could be used to analyze the samples for elemental composition and calorific value.

The analytical procedures are detailed in the ENFOR document "A Workbook for Biomass Gasifier Sampling and Analysis" (Techwest, 1983). Extensive use was made of methods developed by the American Society for Testing and Materials, "Annual Book of ASTM Methods", for analysis of gas, particulate, tar and feed samples. Procedures from the American Public Health Association's "Standard Methods for the Examination of Water and Wastewater" were used for most of the analyses of the aqueous condensate.

Results obtained with samples from the B.C. Research gasifier, during the development of these procedures, are described in the document "Development of Sampling and Analytical Procedures for Biomass Gasifiers" (Aiken, 1983).

4.0 WORKBOOK FOR BIOMASS GASIFIER SAMPLING AND ANALYSIS

Upon completion of the development and testing of the sampler and analytical procedures, a Workbook was prepared which presents the procedures used to test biomass gasifiers. This ENFOR document is titled "A Workbook for Biomass Gasifier Sampling and Analysis" (Techwest, 1983).

The Workbook provides a methodology for the following procedures.

a. Obtaining an accurate sample of the raw producer gas. The components of this sample consist of:

   i. coarse particles and/or aerosols as they exist at the sampling temperature,

   ii. fine particles and those tars which condense at or above 200°C,

   iii. tars and aqueous condensate which condense below 200°C,

   iv. noncondensable, dry producer gas.

b. Measuring the total flow rate of the gas streams entering and leaving the gasifier system. Alternately, these flows may be estimated using elemental mass balances.

c. Recovering and analyzing the components of the product stream for mass concentration, elemental composition and calorific value.

d. Using these data to calculate mass balances, energy balances, net conversion efficiency and gross conversion efficiency.

e. Analyzing the aqueous condensate for phenolics, organic acids, alcohols and other components.

f. Modifying a commercial high volume stack sampler to enable it to sample the hot gases and tarry residues.

This Workbook describes the procedures for gasifier sampling in fine detail. The quality and amount of data and information obtained through the use of these procedures may not always be required by a gasifier operator. A simplified procedure for obtaining mass and energy balances is being prepared as an additional ENFOR project.

5.0 FIELD TESTING OF WORKBOOK METHODOLOGY

To evaluate the application of the Workbook methodology, a field trial was conducted using Forintek's downdraft gasifier located in Ottawa.

The field trial showed that the Workbook procedures, developed using a fluidized bed gasifier, could also be successfully applied to a downdraft gasifer. The document "Testing the Prototype Sampler on a Downdraft Biomass Gasifier" describes the results of the field trials (Aiken, 1983).

Three runs were carried out. The overall and element mass balances calculated for the last two runs are given in Table 4. (Balances were not computed for Run 1 due to a problem with leakage from the flare bypass during the run).

Carbon balances of 97 and 104% were achieved. The nitrogen balance and consequently the overall balance were high by 15 to 25%. This discrepancy suggests an error in the estimate of the blower air rate. The evidence for this suggestion is based on the data in Tables 5 and 6, which show detailed information on the contribution of inflow and outflow streams to mass, energy and element balances which can be obtained by application of the Workbook methodology. The nitrogen balance has one major input and one output source. The nitrogen in the dry, clean gas can be reliably measured, therefore, a balance which deviates from 100% indicates an error in the measurement of the input air flow.

The information in Tables 5 and 6 can also be used to make reliable judgements on the effect of not collecting and analyzing one or more components of the producer gas. For the Forintek gasifier, not analyzing the particulates, tar and

condensate would remove 10% of the mass balance contribution. An energy balance of no better than 88% would be achieved if these three fractions were not analyzed. With the Workbook procedures, energy balances as percent closure, Table 7, for the Forintek downdraft gasifier were 86% for Run 2 and 95% for Run 3. The associated net energy conversion efficiencies were 60% and 66%, respectively.

6.0 ANALYSIS OF CONDENSATE AND TAR

Condensate samples were analyzed for phenols, acetic and propionic acids, methanol, acetone, formaldehyde and tannin and lignin. An example of the results for the condensates obtained from the Forintek downdraft gasifier is shown in Table 8. The compounds identified amounted to about 70% of the organic material present in the condensate, as indicated by the identified carbon computed as a percentage of the total carbon measured by Total Organic Carbon (TOC) analysis.

The analysis of gasifier tars, to identify the major components, has been shown to require fairly sophisticated techniques. Previous work at B.C. Research, using column chromatography to achieve fractionation of gasifier tars, was not able to achieve separation of the complex mixtures into clean fractions (Duncan, 1981). Under the ENFOR biomass conversion program, a number of groups are working on the analytical procedures for determination of the composition of wood oils derived from the liquefaction of wood. One group at the University of Sherbrooke, under the direction of Dr. Hughes Ménard, has successfully developed a fractionation procedure utilizing high performance liquid chromatography with subsequent identification using gas chromatography/mass spectroscopy (Ménard, 1982). Dr. Ménard has shown that these procedures are applicable to the fractionation and identification of gasifier tar components, using a tar sample from the B.C. Research gasifier. Unfortunately, time constraints have prevented Dr. Ménard from completing the work in time for publication in this report. Qualitative analysis of the first fraction, eluted with 100% pentane, has been completed. The information which Dr. Ménard has obtained is summarized in Table 9.

Analysis for acids in the pentane fraction of the B.C. Research gasifier tar showed that the tar contained mainly propionic acid (5.34%) with traces of formic and acetic acids. Analysis of condensates from the Forintek gasifier showed mainly acetic acid, 3 to 8%, small amounts of propionic acid, 0.2 to 0.9%, and no formic acid. Therefore, it appears that acetic and propionic acids are the main acids produced during the gasification process, with acetic acid recovered in the aqueous condensate and propionic acid condensing with the tar fraction.

Samples of tars from the B.C. Research and Forintek gasifiers were analyzed by gas chromatography for polycyclic aromatic hydrocarbons by a gas chromatographic procedure used at B.C. Research to analyze coal tar liquids. The results of these analyses are shown in Table 10. Many polycyclic aromatic hydrocarbons were identified in the tar samples, among them benzo(a)pyrene which is a known human carcinogen. The prefilter tar sample from the Forintek gasifier contained lower amounts of all these compounds than the postfilter sample. The B.C. Research sample and Forintek postfilter sample had similar concentrations for many of the compounds listed. It is noted in this table where Dr. Ménard's results support the identification of a compound. A typical chromatogram of the tar samples, in this example a postfilter sample from the Forintek gasifier, is shown in Figure 3. Most of the major peaks in the chromatogram have not been identified. The Forintek prefilter tar sample and the B.C. Research tar sample showed similar unidentified major peaks. Budget restraints prevented the continuation of this work to identify these components.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The procedures detailed in "A Workbook for Biomass Gasifier Sampling and Analysis" were successfully applied to both a downdraft and fluidized bed gasifier. Reliable mass and energy balances were achieved for each gasifier.

The sampler proved effective in obtaining representative raw producer gas samples. The presence of tarry residues did not affect the operation of the sampler. The sampler separated dry, clean gas from these tarry residues and effected a partial separation of the residues. Subsequent separation of particulates, tar and condensate into discrete, homogeneous fractions was readily achieved. These fractions were then analyzed by standard analytical procedures.

The Workbook procedures provide a wealth of information about the operation of the gasifier. For research applications this methodology provides both the quality and quantity of data required for informed judgements. However, for routine, non-research application this methodology may be too complex and, hence, a simplified procedure for obtaining mass and energy balances is being developed.

The application of this Workbook methodology is not limited to biomass gasifiers. It can be applied to any operation where the producer gas either contains tarry residues or is hot, for example, coal gasification processes.

8.0 REFERENCES

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Techwest Enterprises. 1983. A Workbook for Biomass Gasifier Sampling and Analysis. ENFOR Project C-172, March.

FIGURE 1

GASIFIER SAMPLING TRAIN
(SCHEMATIC)

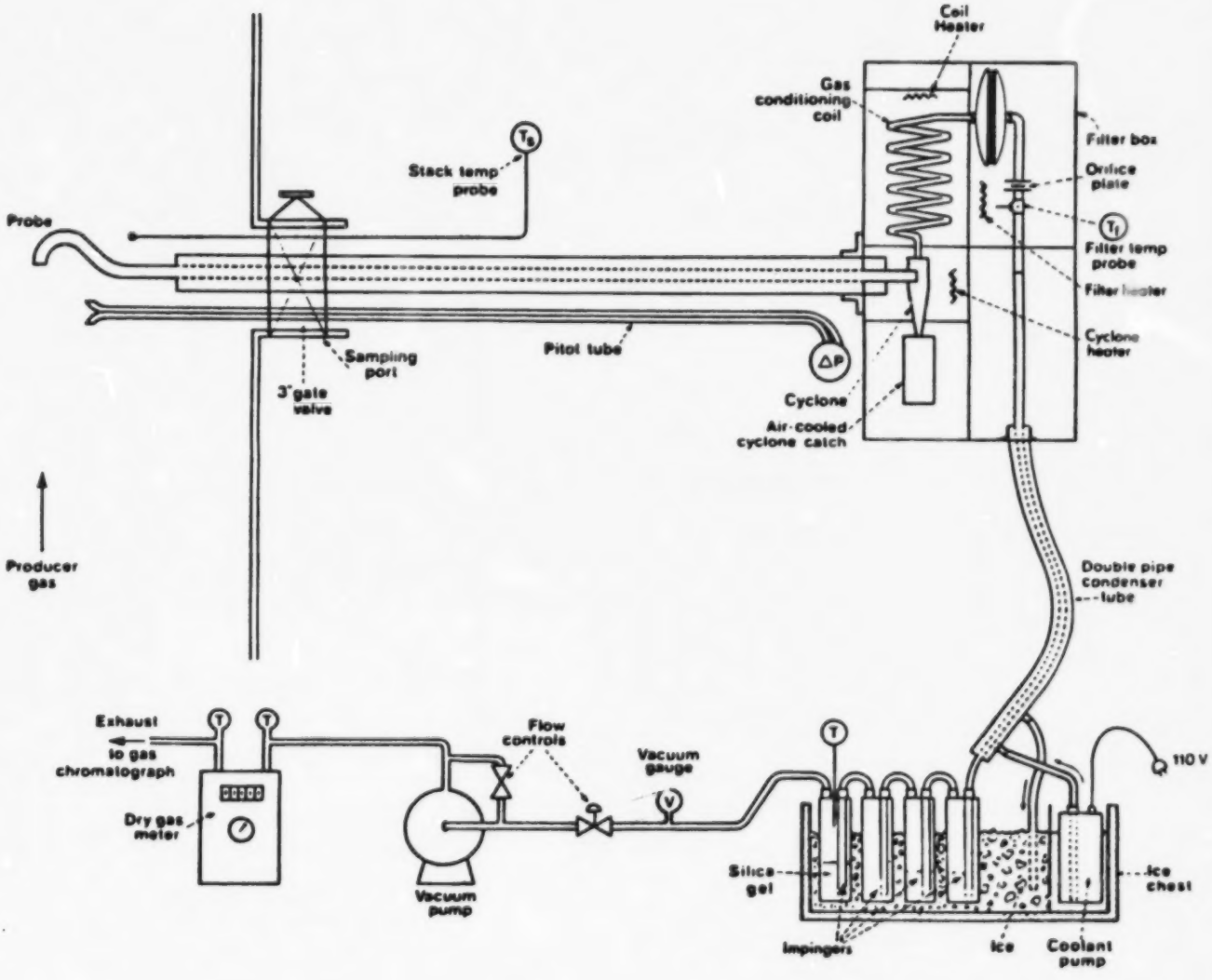


FIGURE 2

GASIFIER SAMPLER

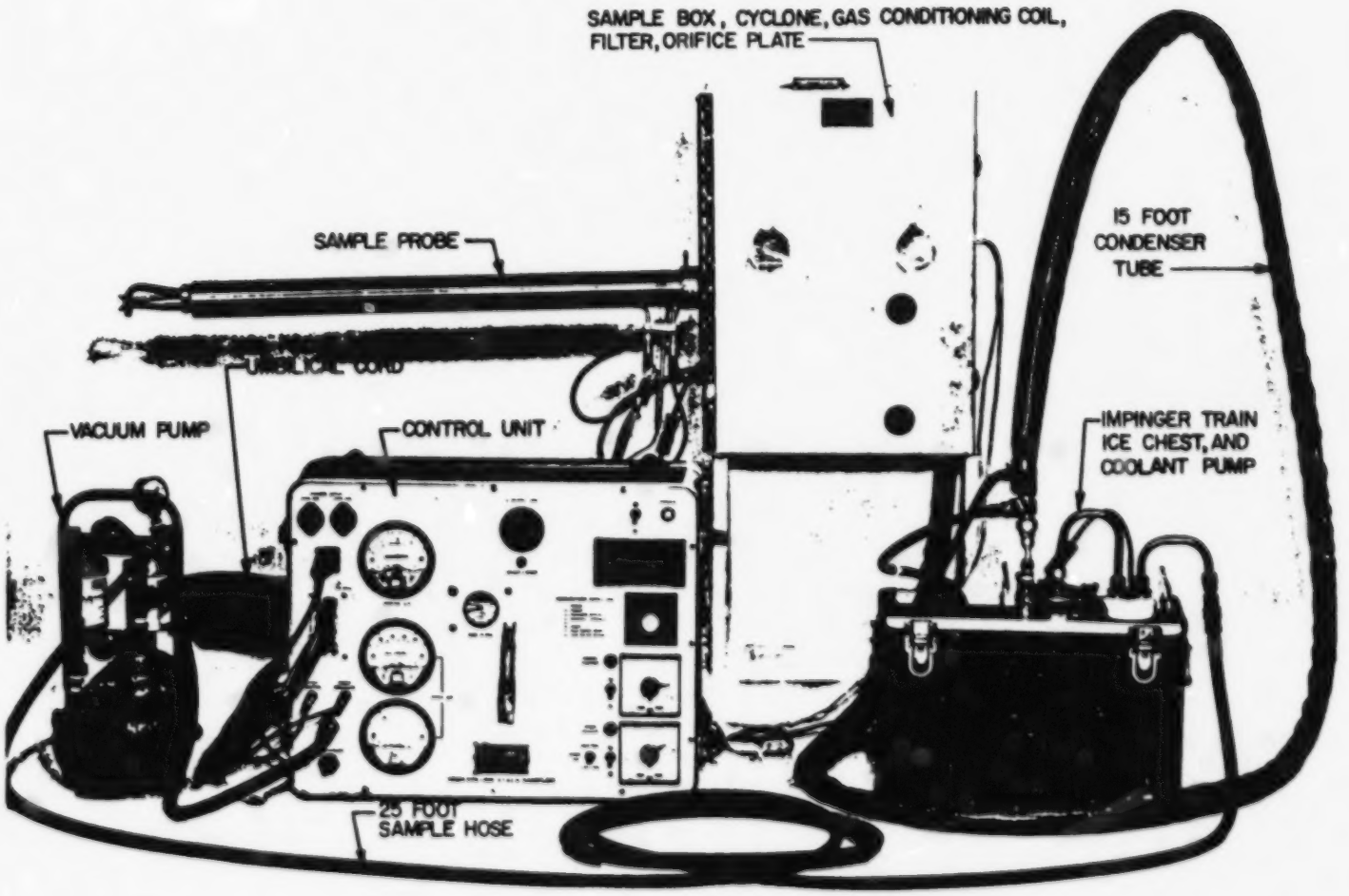
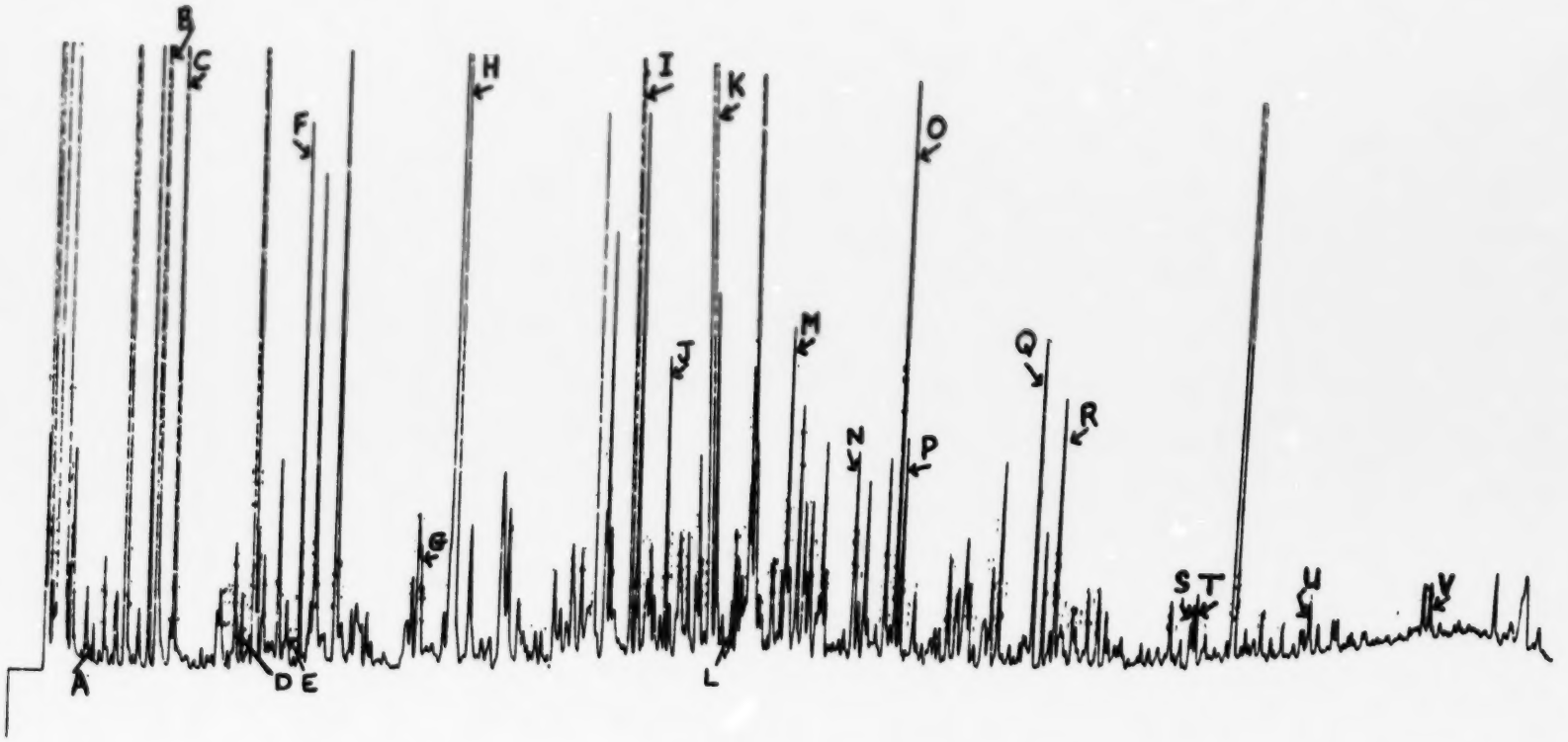

SAMPLE BOX, CYCLONE, GAS CONDITIONING COIL, FILTER, ORIFICE PLATE
SAMPLE PROBE
UMBILICAL CORD
VACUUM PUMP
CONTROL UNIT
15 FOOT CONDENSER TUBE
IMPINGER TRAIN ICE CHEST, AND COOLANT PUMP
25 FOOT SAMPLE HOSE

FIGURE 3

CHROMATOGRAM OF GASIFIER TAR SAMPLE
FORINTEK DOWNDRAFT GASIFIER: POST FILTER



A Toluene
B m-,p-xylene
C o-xylene
D Trimethyl benzene
E p-cymene
F Indene
G Tetralin
H Naphthalene

I Tridecane (ISTD)
J Biphenyl
K Acenaphthylene
L Acenaphthene
M Fluorene
N 9,10-dihydro-phenanthrene

O Phenanthrene
P Anthracene
Q Fluoranthene
R Pyrene
S Benz(a)anthracene
T Chrysene
U Benzo(k)fluoranthene
V Indeno (1,2,3-cd) pyrene

TABLE 1

SUMMARY OF SAMPLING TESTS: B.C. RESEARCH FLUIDIZED BED GASIFIER

RUN	DATE 1982	LOCATION	GASIFIER PARAMETERS					SAMPLING CONDITIONS			Particulate Emissions
			Inflow Volume m^3/hr	Exit Volume m^3/hr	Sampling Location Temp. °C	Bed Temp. °C	Upper Free-Board Temp. °C	Flowrate m^3/hr	Time min.	Volume m^3	kg/hr
1	5/26	Gasifier Discharge	102	-	estimated 225	714	557	0.578	45	0.411	-
2	5/28	"	119	-	142	223	454	0.578	45	0.450	-
3	6/1	"	106	-	216	711	542	0.357	65	0.377	-
4	6/2	"	119	119	277	691	637	0.102	45	0.722	1.22
5	6/3	"	116	117	estimated 285	746	651	2.96	40	1.94	0.771
6	6/8	Gasifier free-board	124	151	636	723	602	1.00	45	0.679	1.32
7	6/22	"	110	121	538	720	513	0.985	72	1.22	2.09
8	6/29	"	133	127	601	785	602	1.53	29	0.716	0.771

(a) Based on 1 atmosphere and 15°C.

TABLE 2

MASS AND ENERGY BALANCE SUMMARY: B.C. RESEARCH FLUIDIZED BED GASIFIER

RUN	MASS BALANCE Closure %					ENERGY BALANCE		
	Overall	C	H	O	N	Gross Energy Balance Closure %	Energy Conversion Efficiency, %	
							Gross	Net
4	89	96	104	105	76	74	73	46
5	88	93	93	105	75	65	64	42
6	105	90	135	107	104	101	101	47
7	89	95	105	90	85	92	92	51
8	83	103	97	86	76	91	91	52

TABLE 3

CONTRIBUTION OF INFLOW AND OUTFLOW STREAMS
TO MASS, ENERGY AND ELEMENT BALANCES: B.C. RESEARCH
FLUIDIZED BED GASIFIER

Description	Mass Balance %	Energy Balance %	Carbon %	Hydrogen %	Oxygen %	Nitrogen %
INPUT						
dry feed	20.7	99.1	100.0	57.3	28.3	0.1
moisture in feed	7.9	0.1	0	40.0	21.1	0
air	70.8	0	0	0	49.1	99.9
moisture in air	0.6	0	0	2.7	1.5	0
(process energy)		0.8				
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0
OUTPUT						
dry clean gas	82.9	71.0	88.1	29.2	61.1	99.9
moisture in gas	14.8	13.0	0	63.1	37.7	0
particulates	0.4	1.0	1.6	0	0.1	0
tar	1.6	13.5	9.3	6.9	0.9	0
condensate	0.3	1.4	1.0	0.8	0.2	0.1
(process energy)		0.1				
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 4

FORINTEK DOWNDRAFT GASIFIER MASS BALANCES

RUN 2 (Date: 10/28/82)

	kg/hr INPUT		kg/hr OUTPUT		% CLOSURE
	Fuel	Air	Clean Gas	Others	
Overall	83.73	68.47	135.94	39.06	115.0
Carbon	36.87	0	27.19	8.66	97.2
Hydrogen	5.73	0.05	2.67	2.49	89.3
Oxygen	41.14	16.20	42.06	17.94	104.6
Nitrogen	0.04	52.22	64.03	0.02	122.6

RUN 3 (Date: 10/29/82)

	kg/hr INPUT		kg/hr OUTPUT		% CLOSURE
	Fuel	Air	Clean Gas	Others	
Overall	73.02	62.41	127.19	42.57	125.3
Carbon	31.66	0	25.12	7.88	104.2
Hydrogen	4.90	0.05	2.63	2.46	102.8
Oxygen	36.46	14.74	39.45	18.29	112.8
Nitrogen	0.03	47.62	59.99	0.02	125.9

TABLE 5

CONTRIBUTION OF INFLOW AND OUTFLOW STREAMS TO MASS, ENERGY AND ELEMENT BALANCES:
FORINTEK DOWNDRAFT GASIFIER
RUN 2

	MASS BALANCE %	ENERGY BALANCE %	CARBON %	HYDROGEN %	OXYGEN %	NITROGEN %
INPUT						
Dry Feed	50.4	99.8	100.0	85.6	60.9	0.1
Moisture in Feed	4.6	0	0	13.5	10.9	0
Air	44.7	0	0	0	27.5	99.9
Moisture in Air	0.3	0.1	0	0.9	0.7	0
(Process Energy Input)	-	0.1	-	-	-	-
Total	100.0	100.0	100.0	100.0	100.0	100.0
OUTPUT						
Dry Clean Gas	77.7	71.0	75.8	51.7	70.1	100.0
Moisture in Gas	9.8	3.6	0	36.8	25.4	0
Particulates	0.1	0.2	0.4	0.2	0.1	0
Tar	1.8	7.2	6.2	5.8	1.0	0
Condensate	7.4	4.8	4.1	4.7	2.6	0
Char	2.8	11.8	12.6	0.4	0.4	0
Fly Ash	0.3	0.9	0.9	0.2	0.2	0
Moisture in Char and Fly Ash	0.1	0	0	0.2	0.2	0
(Process Heat Loss)	-	0.5	-	-	-	-
Total	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 6

CONTRIBUTION OF INFLOW AND OUTFLOW STREAMS TO MASS, ENERGY AND ELEMENT BALANCES:
FORINTEK DOWNDRAFT GASIFIER
RUN 3

	MASS BALANCE %	ENERGY BALANCE %	CARBON %	HYDROGEN %	OXYGEN %	NITROGEN %
INPUT						
Dry Feed	48.2	99.8	100.0	81.6	57.9	0.1
Moisture in Feed	5.7	0	0	17.4	13.4	0
Air	45.8	0	0	0	28.1	99.9
Moisture in Air	0.3	0.1	0	1.0	0.6	0
(Process Energy Input)	-	0.1	-	-	-	-
Total	100.0	100.0	100.0	100.0	100.0	100.0
OUTPUT						
Dry Clean Gas	74.9	71.9	76.1	51.7	68.3	100.0
Moisture in Gas	10.8	4.2	0	40.1	28.3	0
Particulates	0.2	0.2	0.6	0.2	0.2	0
Tar	1.4	5.3	5.0	4.7	0.9	0
Condensate	9.2	3.3	2.6	2.9	1.6	0
Char	3.2	14.0	15.0	0.4	0.4	0
Fly Ash	0.2	0.6	0.7	0	0.1	0
Moisture in Char and Fly Ash	0.1	0	0	0	0.2	0
(Process Heat Loss)	-	0.5	-	-	-	-
Total	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 7

FORINTEK DOWNDRAFT GASIFIER ENERGY BALANCES
RUNS 2 AND 3

RUN #	INPUT (MJ/hr)						OUTPUT (MJ/hr)							
	Fuel	%	Air	%	Others	%	Clean Gas	%	Tar Particulates Condensate	%	Others	%	% CLOSURE	
2	1468.54	99.8	0.81	0.06	1.61	0.11	945.75	74.6	155.04	12.2	167.31	13.2	86.2	
3	1243.70	99.8	0.76	0.06	1.61	0.13	900.22	76.1	104.27	8.8	178.67	15.1	95.0	
	GROSS ENERGY CONVERSION EFFICIENCY													GROSS ENERGY CONVERSION EFFICIENCY %
2	1468.54	99.8	0.81	0.06	1.61	0.11	945.75	85.9	155.04	14.1	0	0	-	74.8
3	1243.70	99.8	0.76	0.06	1.61	0.13	900.22	89.6	104.27	10.4	0	0	-	80.6
	NET ENERGY CONVERSION EFFICIENCY												CONVERSION	NET ENERGY EFFICIENCY %
2	1468.54	99.8	0.81	0.06	1.61	0.11	878.77a	100.0	0	0	0	0	- -	59.7
3	1243.70	99.8	0.76	0.06	1.61	0.13	825.94a	100.0	0	0	0	0	- -	66.3

a) Heat of combustion; dry, clean gas

TABLE 8

COMPOSITION OF CONDENSATES: FORINTEK DOWNDRAFT GASIFIER

Compound	Run 1		Run 2		Run 3	
	g compound/ 100 mL condensate %	g carbon/ 100 g TOC (a) %	g compound/ 100 mL condensate %	g carbon/ 100 g TOC %	g compound/ 100 mL condensate %	g carbon/ 100 g TOC %
Phenols (as phenol)	0.45	6.81	0.72	4.92	0.50	6.89
Acetic Acid	3.67	28.8	7.60	27.1	4.29	30.9
Propionic Acid	0.19	1.76	0.89	3.87	0.45	3.93
Methanol	1.46	10.7	2.52	8.41	1.53	10.3
Acetone	0.13	1.61	0.51	2.85	0.35	3.97
Formaldehyde	1.47	11.5	4.07	14.5	1.77	12.8
Tannin and Lignin (as tannic acid) (b)	0.63	6.42	2.26	10.5	0.70	6.62
Unknown	-	32.4	-	27.8	-	24.5

a) TOC: Total Organic Carbon
b) nonvolatile hydroxylated aromatics

TABLE 9

RESULTS OF TAR ANALYSIS BY HIGH PERFORMANCE LIQUID CHROMATOGRAPHY
B.C. RESEARCH GASIFIER TAR SAMPLE
- RESULTS FROM DR. HUGHES MENARD,
UNIVERSITY OF SHERBROOKE

A. WATER DETERMINATION

3.1% by weight of tar by Karl Fischer Technique

B. ELEMENTAL ANALYSIS

74.6% carbon
8.2% hydrogen
1.2% nitrogen
16.0% oxygen (by difference)

C. ACID ANALYSIS

Compound	% of tar by weight
Glycolic acid	0.00
Formic acid	0.17
Acetic acid	0.06
Propionic acid	5.34
Butyric acid	0.19
Pentanoic acid	0.39
Hexanoic acid	0.59
Heptanoic acid	0.55

D. NMR C^{13} ANALYSIS

Aromatic carbon	35.79% by weight
Aliphatic carbon	53.59%
Carbon tentatively allocated to sugars	7.43%
Carbonyl carbon	3.17%

E. FRACTIONATION

Solvent	% of Tar by Weight in Fraction
100% Pentane	31.0
100% Tetrahydrofuran	32.8
100% Methanol	2.9
100% Water	0.6
50% Water-50% Acetic Acid	10.3
Material retained on the column or lost during evaporation of solvent	22.4

TABLE 10

ANALYSIS OF TAR BY GAS CHROMATOGRAPHY
IDENTIFICATION OF POLYCYCLIC AROMATIC HYDROCARBONS

Compound	B.C. Research Gasifier Tar Sample mg/g	Forintek Gasifier Tar Samples	
		Prefilter mg/g	Postfilter mg/g
Toluene	nd[a]	0.031	nd
m-,p-xylene	0.34	6.10	13.21
o-xylene	0.20	6.93	9.26
Cumene	0.56	0.075	nd
Trimethyl benzene	nd	0.60	0.32
p-cymene	0.24	nd	0.59
Indene	3.29	0.12	3.07
Tetralin	0.36	nd	0.88
Naphthalene[b]	10.60	0.47	16.18
Biphenyl[b]	c	0.50	1.30
Acenaphthylene[b]	4.23	0.082	8.65
Acenaphthene[b]	0.44	0.013	0.55
Fluorene	1.21	0.071	1.87
9,10-dihydrophenanthrene	0.90	0.43	6.95
Phenanthrene[b]	2.63	0.048	3.76
Anthracene[b]	1.04	0.027	1.06
Fluoranthene[b]	0.89	0.036	1.57
Pyrene[b]	0.77	0.031	1.27
Benz(a)anthracene[b]	0.36	0.023	0.33
Chrysene	0.36	0.011	0.36
Benzo(k)fluoranthene	0.20	0.015	0.17
Benzo(b)fluoranthene	0.59	0.043	nd
Benzo(a)pyrene	0.21	0.033	nd
Indeno(1,2,3-cd)pyrene	0.21	0.037	0.36
Benzo(ghi)perylene	0.18	0.027	nd

a. not detected
b. presence of compound confirmed by GC-MS analysis carried out by Dr. Hughes Ménard, University of Sherbrooke
c. large peaks either side of biphenyl peak prevented quantification.

POOR

QUALITY

ORIGINAL